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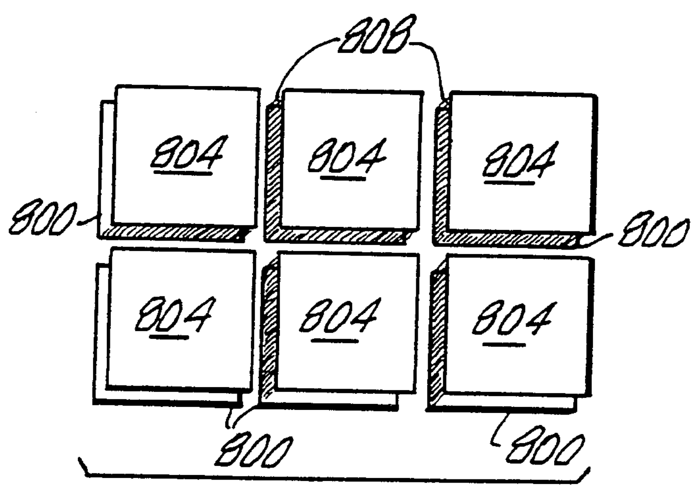

(57) Abstract

Improved methods for stereolithographically making an object by alternating the order in which similar sets of vectors are exposed over two or more layers. In another method, a technique for closing the gaps between tiles (800, 804) wherein before closure each tile (800, 804) is isolated from its neighboring tiles (800, 804) by specifying breaks of unexposed material (808) between the tiles (800, 804). Using an interrupted scan method, vectors are drawn with periodic breaks along their lengths. Modulator and scanning techniques are used to reduce exposure problems associated with the acceleration and deceleration of the scanning system when jumping between vectors or changing scanning directions.

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DESCRIPTION

METHOD OF AND APPARATUS FOR MAKING A THREE-DIMENSIONAL OBJECT BY STEREOLITHOGRAPHY

Technical Field of the Invention and Background Art

This invention relates to the field of stereolithography, which is a technique for making solid, three-dimensional objects (or "parts") from solidifiable materials (e.g. fluid or fluid-like materials such as photopolymers, sinterable powders, and bindable powders) on a layer by layer basis. More particularly this invention relates to improved methods and apparatus for successively exposing layers of stereolithographic building materials to form the layers of stereolithographic parts with less distortion.

In recent years, stereolithography systems, such as those described in U.S. Pat. No. 4,575,330, have come into use. Basically, stereolithography is a technique for automatically building complex three-dimensional parts by successively and selectively solidifying and adhering a plurality of thin cross-sectional layers, wherein each thin cross-section formed represents a corresponding cross-sectional region of the three-dimensional object. These layers are composed of a material that can be selectively transformed from a fluid-like state to a solid, or cohesive, state upon exposure to synergistic stimulation. The layers are typically solidified on top of each other consecutively until all of the thin layers are joined together to form a whole part.

The material is typically composed of liquid polymer resins, e.g. photopolymers or thermosetting polymers, powdered materials, or the like. Typical powders include waxes, thermoplastics, metals, ceramics or the like. The solidification mechanism can be sintering or melting followed by bonding of particles upon cooling and resolidification. The sintering or melting can be induced by

synergistic stimulation in the form of heat. For example, the heat can be IR radiation generated by a laser or it can be frictionally induced by ultrasonic vibration.

Another solidification mechanism uses an adhesive binder to form thin layers of solid. The binder is selectively dispensed, e.g. by ink jet or the like, into a thin layer of powder thereby bonding the powder particles together. The particle diameter is preferably smaller than the desired formation resolution, more preferably smaller than half the desired resolution and most preferably smaller than one tenth the desired resolution. Many photopolymers have a photospeed (rate of transformation from liquid to solid) upon irradiation with ultraviolet light (UV) which is fast enough to make them practical model building materials, such as acrylic or urethane based materials, e.g. XB 5143 produced by Ciba Geigy of Switzerland. In a preferred system, a radiation source (e.g., a HeCd or Argon Ion ultraviolet laser) generates a beam which is focused to a small intense spot which is moved across the liquid photopolymer surface by galvanometer or servo type mirror x-y scanners. The scanners are driven by computer generated vectors. In another embodiment masks and flood exposure are used to cause selective solidification of the material. The material that is not polymerized when a part is made is reusable and remains in the vat for use as successive parts are made.

Stereolithography represents an effective way to quickly make complex or simple parts without tooling. Since this technology depends on using a computer to generate its cross-sectional patterns, there is a natural data link to computer aided design and manufacture (CAD/CAM). However, such systems have presented challenges relating to structural stress, shrink-age, curl and other distortions, as well as resolution, speed, accuracy and difficulties in producing certain object shapes.

Related Patents and Applications

Additional stereolithographic information is supplied in the following patent publications and applications all of which are incorporated herein by reference: U.S. Patent Nos. 4,575,330; 4,929,402; 4,996,010; 4,999,143; 5,015,424; 5,058,988; 5,059,021; 5,059,359; 5,076,974; and 5,104,592; PCT Application Nos. PCT/US89/01558; PCT/US89/-01561; PCT/US89/01559; PCT/US89/01562; PCT/US89/01560; PCT/US89/01557; PCT/US89/04096; PCT/US90/03002; PCT/US90/-05288; PCT/US90/06293; and PCT/US91/08110.

Disclosure of the Invention

One aspect of this invention involves exposing the building material to synergistic stimulation to cause solidification of the building material wherein the exposure of solid lines, e.g. vectors, of material is interrupted in a regular or irregular pattern so that the formation of long lines of material are avoided. This reduces long line pulling effects that can lead to excess distortion of the three-dimensional object being formed. Preferably the lines are formed with a cure depth that doesn't cause adhesion to the previous layer at least on the first exposure.

A second aspect of the invention involves closing gaps between tiles by exposing at least some of the regions over the gaps in a manner which allows the material over the gap to at least partially shrink prior to causing the solidifying material to adhere to the tiles on both sides of the gap. The solidifying material may be adhered to the tile on one side of the gap prior to allowing it to shrink followed by causing adhesion to the tile on the other side only after a substantial portion of the shrinking has occurred.

A third aspect of the present invention involves reducing distortion of stereolithographically produced parts by alternating the curing sequence from layer to layer to uniformly distribute any imbalances in cure which

can otherwise result. An additional embodiment of the third aspect of this invention is tailoring the drawing order and vector types for a given part geometry to deemphasize curl along a given axis. An additional embodiment of the third aspect of this invention involves formation of at least a portion of a three-dimensional object using the Star Weave building method wherein a Weave building style is used with the addition of the use of at least two non-parallel hatch types on each layer, offsetting the hatch vectors from layer to layer, the retraction of one end of each hatch vector from a boundary, and the alternate sequencing of the drawing order.

A fourth aspect of the invention involves the utilization of modified vector scanning techniques which allow most if not all significant decelerations and accelerations of the scanning beam to occur when the beam is shuttered so that constant exposures can be achieved along the entire lengths of vectors and thus uniform cure depths can be achieved.

A fifth aspect of the invention involves combinations of the above four aspects to enhance part producibility still further. For example, the modified vector scanning techniques of the fourth aspect of the invention can be used to improve the results obtainable by the other three aspects. In particular limiting significant decelerations and accelerations to non-exposure times result in more uniform cure depths that can be used to insure that the floating vectors of the retracted Starweave building technique do not unintentionally or prematurely adhere to the previous layer. This allows them to freely shrink without inducing curl into a previous layer.

The invention includes both methods and apparatus for the above aspects.

Brief Description of the Drawings

FIGURES 1a and 1b are top views of vectors scanned respectively according to a first pass of an offset weave

square tiled exposure pattern and according to both passes of an offset weave square tiled exposure pattern.

FIGURES 2a, 2b, and 2c are top views of vectors scanned respectively according to a first pass of an offset-weave hexagonal-tiled exposure pattern and according to both passes of an offset-weave hexagonal-tiled exposure pattern and according to both passes of an alternative offset-weave hexagonal-tiled exposure pattern.

FIGURE 3 depicts the currently utilized conventional scanning order for fill and hatch vectors.

FIGURES 4a and 4d depict respectively each of the scanning patterns of a four-layer sequence of cross-sections utilizing the drawing order of alternate sequencing example #2.

FIGURES 5a to 5h depict respectively each of the scanning patterns for an eight-layer sequence of cross-sections utilizing the drawing order of alternate sequencing example #3.

FIGURES 6a, 6b, and 6c depict the gaps between tiling on a first layer being filled in on a second layer with slightly offset tiles followed by grouting between the offset tiles.

FIGURE 7 depicts closing gaps between tiles on a first layer with an at least partially floating member on a second layer which floating portion is riveted to an adjacent tile on the first layer.

FIGURES 8a to 8g depict various orientations of vectors n and n+1 along with various virtual scanning paths that can be followed to scan from vector n to vector n+1.

Modes For Carrying Out The Invention

The first aspect of the present invention involves methods and apparatus for enhancing part accuracy by providing improved stereolithographic vector scanning procedures known as "Interrupted Scan".

"Interrupted Scan" refers to scanning at least a

portion of a layer to solidify material to form a portion of a three-dimensional object by exposing at least one vector with one or more gaps along its length to relieve transmitted stress. The portions of the vector intended to cause solidification of material can be formed consecutively along the length of the vector, interspersed between exposed portions of other vectors, or by non-consecutively forming all portions of vector prior to forming any portions of a second vector.

Long vectors can cause tremendous amounts of curl if they are cured and adhered to a previous layer while they are still shrinking. This stress-inducing adhesion to the previous layer can occur along the length of the vector. In the case of a floating vector, if a retracted vector embodiment isn't being utilized, it may occur where the ends of the vector attach to a boundary.

In the "interrupted scan" technique, vectors are drawn with periodic breaks along their lengths. The interrupted vectors can be formed in a single pass embodiment where adhesion to the previously formed layer of solidified material occurs upon exposure to the first pass. Alternatively, and more preferably, a multipass embodiment is utilized wherein adhesion to the previous layer doesn't occur upon the first pass but instead occurs on a later pass. In the multipass embodiment the multiple exposures can occur by rescanning the same vector multiple times or alternatively by scanning different paths that overlap at one or more points, thereby resulting in multiple exposures at those points. As with tiling, the exposed length is considerably longer than the gap between breaks. The length of solid between breaks is preferably approximately 2.5 mm to 120mm with the length of the gaps 0.025-0.250mm. The breaks in the vectors can be in a random pattern over the length of a vector, or the breaks in neighboring vectors can form a random pattern. Alternatively, and presently preferred, are methods utilizing breaks formed in a regular or at least predictable manner. The individ-

ual fragmented vectors can either be cured to a depth which causes adhesion or they can be cured to a lesser depth and thereby remain floating or one end can be adhered to the previous layer with the vast majority of the vector floating. The later two options are most preferred.

A first "interrupted scan" method superimposes the interrupted scan over a Weave exposure pattern. The Weave building or exposure technique is described in U.S. Patent Application 07/702,031 and in PCT Patent Application PCT/US90/06293. The Weave building technique exposes cross-sections with at least two types of non-parallel hatch vectors wherein effective adhesion (that capable of transmitting significant curl) only occurs at the overlapping points between the vectors of the two hatch types. Additionally the hatch vectors of each type are spaced as close together as possible without being spaced so close that they can induce curl into adjacent vectors or have curl induced in them by adjacent vectors.

A first embodiment of weaved-interrupted scan is to scan a first pass over a grid of tiles (the floating pass) followed by a second pass over a second grid of tiles to complete the weave. The second grid of tiles is offset from the first grid and is exposed after sufficient delay to allow the fragmented vectors of the first pass to shrink before adhesion to each other or to the previous layer. This is especially favorable when using a hexagonal tile pattern. To remove the possibility of favored axes, the hexagonal grid can be rotated between passes as well as offset or alternatively the hexagonal grid can be rotated or translated from layer to layer.

FIG. 1a depicts a top view of cured material after a first pass over a square tiling grid. FIG. 1b depicts the same top view after a second pass over an offset square tiling grid. As can be seen in FIG. 1b, this offset-weaved tile pattern still potentially contains two weak axes.

FIGS. 2a, 2b, and 2c are similar to FIGS. 1a and 1b, but they utilize a hexagonal tile grid. As can be seen in FIG. 2b, the hexagonal offset-weaved tile pattern has no long straight weak axes. FIG. 2c depicts an alternative offsetting technique wherein the hexagonal tile grid is rotated as well as offset. Since the length and width of hexagons are not equal, the method depicted in FIG. 2c does not form a simple recursive pattern.

There are several ways of implementing the interrupted scan aspect of the present invention. One implementation involves controlling the scanning system as if no interruption was anticipated in conjunction with the placement of a physical barrier, e.g. a mask, between the scanning mirrors and the surface of the building material. For example, this physical barrier can take the form of a grid pattern which selectively blocks the beam thereby causing the formation of breaks in the cured material. This barrier can be selectively moved in and out of place as needed.

A second implementation involves supplying control information to the scanning mirror and shuttering system to cause selective exposure of the medium. The control information can be supplied from a program which creates vectors with breaks or which inserts breaks into vectors which are created and supplied by a second program. Alternatively vector information can be supplied without breaks and software or hardware additions to the mirror control system can insert breaks into the vectors simultaneously with the scanning of the vectors. This last alternative is the preferred approach since it drastically reduces the number of vectors which must be stored and processed. Another implementation would use a pulsed laser for exposing the material wherein the laser's duty cycle (pulse pattern) would be modulated by control signals for causing the formation of breaks.

The second aspect of the present invention involves methods and apparatus for enhancing part accuracy by

supplying improved stereolithographic "tiling" procedures. The formation of stereolithographic parts wherein at least portions of one or more layers is exposed in a tiling pattern is disclosed in U.S. Patent Application Serial No. 07/702,031 and in PCT Patent Application Serial No. PCT/US90/06293.

"Tiling" is an interrupted exposure or scanning technique that applies to relatively wide regions as opposed to narrow regions, e.g. lines or vectors. The wide regions may be made up of vectors. The "tile" exposure or scanning results in distinct shapes which fit together very snugly but are not adhered to each other. The intention of this method is to maximize the percentage of material cured in the building process while maintaining the curl at a reasonable level by reducing transmitted stresses that generate curl. A potential disadvantage of tiling is that it can possibly provide parts with less green strength. This disadvantage can be partially overcome by curing the material between the tiles, i.e. grouting, after the tiles have been formed. Green strength can be increased by this technique but at least some curl distortion is reintroduced.

After forming one or more layers with tiling and without grout, it is generally desirable to start offsetting tiles from layer to layer or to begin grouting between tiles or to stop the tiling process altogether in order to insure adequate structural integrity of the part. However if tiling is to be discontinued, grouted, or offset, it is important to minimize any tendency toward reintroducing curl that may result from closing the gaps. As the gaps are closed, any shrinkage of material that occurs above the gap, while the shrinking material is adhered to both ends of the gap, can cause curl distortion by tending to bring the top ends of the gap closer together (closer than the spacing between the bottom edges of the gap). Since gaps can result in relatively weak axes, reintroducing curl is very likely. Additionally, it has

recently been experimentally verified that shrinkage of curing material can still be occurring several seconds after exposure of an area is suspended. This means that closing a gap with a line of curing material which is adhered to the first side, and extended from the first side to the second side, and adhered to the second side within a few seconds can induce stresses into the part which can lead to distortion.

A preferred technique of closing gaps, and thereby insuring adequate structural integrity of a part, while avoiding reintroduction of curl, is based on insuring that at least a substantial portion of the material cured over the gap is allowed to shrink prior to adhering the cured material over the gap to both sides of the gap.

A first embodiment of this technique slightly offsets the tiles on a second layer from the corresponding positions of tiles on the previous (first) layer. With the offset, the tiles on the second layer substantially cover the gaps between the tiles on the first layer without completely bridging the gap. This avoids the simultaneous adhesion of a single cured shrinking mass to both sides of the gaps on the first layer. After allowing sufficient time for the tiles and the material spanning the gaps to complete their shrinking, grouting is formed between the tiles on the second layer. This grouting completes the bridging of the gap with only minimal shrinkage of material over the gap while adhesion to both sides exists. Since this grouting is offset from the gaps on the first layer, and since shrinkage of material on the second layer over the gaps occurs before the grouting is formed, significantly less curl is introduced. Any desired exposure can be used in forming the grouting, without necessarily being limited to grouting at a lower exposure than the exposure used to cure the tiles.

This first embodiment is shown in Figures 6a to 6c. Figure 6a depicts a side view of a portion of an object comprising a first layer which is formed with tiles 800

and a second layer with slightly offset tiles 804 and offset grout. The tiles 804 of the second layer are offset sufficiently from tiles 800 on the first layer to substantially cover the gap area on the first layer without being offset so far as to adhere to the neighboring tiles on the first layer. The grouting 808 between the tiles 804 on the second layer is solidified after the tiles 804 on the second layer have been allowed to shrink (e.g., generally at least a 3 to 5 second delay between completing neighboring tiles and beginning to grout but delay can vary with material). An acceptable delay time can be determined for a given material, by building one or more test parts, which consist of floating lines of material which are fixed at one end only, and by observing the time required for the lines to complete a substantial portion of their shrinkage. Figure 6b shows a top view of the tiles 800 of the first layer. Figure 6c shows a top view with superimposed tiles 800 of the first layer and tiles 804 of the second layer and the grouting 808 of the second layer.

A second embodiment of this technique forms the second layer, on which the gaps will be closed by floating at least one end of the solidified material which spans the gap until after at least a substantial portion of the shrinkage has occurred. After allowing for shrinkage to occur, the floating end(s) can be tacked down with rivets, or multipass, or the like. Rivets and multipass are disclosed in U.S. Patent 5,104,592 and PCT Patent Application No. PCT/US89/01558.

Figure 7 shows a side view of a gap 810 between tiles 800 on a first layer being closed off on a second layer by floating at least one end of bridging material 814 until the bridging material has completed shrinking. The rivet 818 completes the closure.

Additional embodiments of this technique involve the progressive partial closure of the gaps over a plurality of layers. For example, a gap can be partially narrowed

from one or both sides on a second layer followed by additional narrowing or complete closure on a third or higher layer.

As will be apparent to those of skill in the art these embodiments can be modified or/and combined with themselves or other curl reduction techniques to effectively close gaps without reintroduction of substantial curl.

As with the interrupted scan aspect of this invention, the implementation of the tile closure aspect can be implemented through software or hardware; through control of the scanning system or/and shutter; or by automatically or manually placing an exposure interrupting grid between the scanning mirrors and the surface of the building material and shifting or changing the grid when it is desired to close the gaps formed on a previous layer.

The third aspect of this invention for improving stereolithographically produced parts is known as "Alternate Sequencing" or "Reciprocal Sequencing". This technique is applicable to the various methods of building with continuous skins ("skintinuous"), to the cross-hatched building styles, and to original methods of building completely solid parts. These various building methods are disclosed in U.S. Patent Application Serial No. 07/702,031 and in PCT Patent Application Serial No. PCT/US90/06293. In conventional stereolithography, the vector drawing sequence is substantially identical from layer to layer. This is especially true when considering fill and hatch vectors. The filling vectors on each layer are processed according to the same rules and output in the same order on every layer. For example, this conventional approach may scan a first set of X-hatch vectors starting with the X-hatch vector which is closest to the X-axis (and the origin) followed by scanning successive X-hatch vectors which are further from the axis. After all the X-hatch vectors are processed, then the Y-hatch vectors may be scanned starting with the Y-hatch vector closest to the Y-axis (and the origin) and followed by

those vectors which are successively further away. This conventional approach leads to the same curing and shrinking forces reinforcing each other as successive layers are drawn. This is especially true for identical or nearly identical layers. Therefore, if there are imbalanced forces associated with a particular order of curing, even if these forces are minor, reinforcement from layer to layer can eventually cause enough build up to induce significant levels of stress and distortion in a part. This distortion may be seen in a partially completed part as it builds up or it may be seen shortly after post-curing or after allowing the part to settle after post-curing.

This problem is well known in the art. For example, some symmetrical parts tend to curl in the same region, for no previously explainable reason. An example of this is a part called a SLAB-6. This is a 6-inch by 6-inch by 1/4-inch tall square diagnostic part. On repeated buildings of this part utilizing conventional sequencing rules, the same corner of the part tends to pull away from the supports. The primary difference between the corners of the part is in the order in which they are formed.

A solution to this problem is Alternate Sequencing. Alternate Sequencing is a method of scanning wherein the scanning pattern is intentionally altered from layer to layer thereby leading to more uniform dispersion of stresses that can build up during the curing process. The pattern of alternate sequencing may be random or predictable. It may be periodic or non-periodic.

Presently preferred stereolithographic apparatus, in particular the SLA250 manufactured by 3D Systems, Inc. of Valencia, California, USA, uses a conventional sequencing pattern. At present, the conventional sequencing pattern scans all hatch and fill vectors on all Slice layers in the same sequence. For convenience of description, we assume the machine is oriented so that the front of the

vat is considered South and the back of the vat is considered North, and when facing the front of the vat (looking north) the right side of the vat is East and the left side is West. Specifically in current SLAs, Y vectors are drawn first (they run north and south), starting at the East side of the vat and proceeding towards the West side of the vat. The X-vectors are drawn second (they run east and west) and propagate from North to South. This drawing pattern is shown in FIG. 3 wherein the numbers 1 through 8 indicate the drawing order of the vectors.

A first example of alternate sequencing uses X-hatch and Y-hatch wherein the X-hatch vectors are scanned followed by scanning the Y-hatch vectors on a first layer. Then the Y-hatch vectors are scanned followed by scanning the X-hatch vectors on a second layer and repeating this pattern on alternating layers.

A second example expands the two-layer pattern of the first example into a four-layer pattern. On the first layer, X-hatch is scanned first starting with the vectors closest to the X-axis (and the origin) followed by scanning the Y-hatch vectors starting with the vectors closest to the Y-axis (and the origin). On the second layer, X-hatch vectors are drawn first starting with the vectors furthest from the X-axis (and the origin) followed by scanning the Y-hatch vectors starting with the vectors furthest from the Y-axis (and the origin). On the third layer, the Y-hatch vectors are scanned first starting with those closest to the Y-axis (and the origin) followed by scanning the X-hatch vectors starting with those closest to the X-axis (and the origin). On the fourth and final layer, before repeating the pattern, the Y-hatch vectors are scanned first by starting with those farthest from the Y-axis (and the origin) followed by scanning of the X-hatch vectors by starting with those vectors which are furthest from the X-axis (and the origin). An example of this drawing order for the four characteristic layers of the pattern is depicted in FIG. 4a to 4d, wherein the

numbers 1 through 8 indicate the relative drawing order of the vectors.

A third example is described by the following table and is shown in FIGS. 5a to 5h, wherein the numbers 1 through 8 indicate the relative drawing order of the vectors:

Example 3: An 8-Layer X/Y Reciprocal Sequencing Pattern

FIG. #	Layer Number	Vector Type	Propagation Direction
5a	1	Y	East to West
		X	North to South
5b	2	X	South to North
		Y	West to East
5c	3	Y	East to West
		X	South to North
5d	4	X	North to South
		Y	West to East
5e	5	Y	West to East
		X	South to North
5f	6	X	North to South
		Y	East to West
5g	7	Y	West to East
		X	North to South
5h	8	X	South to North
		Y	East to West

Similar scanning patterns can be developed based on X/60/120 hatch, or other hatch and fill types and other alternative sequences will be apparent to those of skill in the art. For example, if only one vector type is used, the propagation direction can be alternately sequenced. Additionally, as with other aspects of this invention,

other than vector defined paths can be used, for example scanning patterns based on complex curves or the like can be used. Similarly, drawing order can be based on part geometry, wherein a fixed drawing order can be used to emphasize or deemphasize the tendency of an object feature to curl or not to curl along a particular axis. For example, if a cantilever portion of an object is oriented along the x-axis (length along the x-axis larger than length along the y-axis) curl can be reduced along the x-axis by solidifying the cantilever using only vectors oriented along the y-axis. Alternate Sequencing is a powerful tool which leads to more uniform internal stress distributions, reduced distortions during building, and improved overall part accuracy.

Presently, "Starweave", or "Star Weave", is the most preferred building method. This embodiment uses an X/Y WEAVE technique, wherein the WEAVE pattern is STaggered from layer to layer utilizing the above described 8-layer pattern of Alternate sequencing along with the hatch vectors being Retracted from the boundary at their termination points.

In conventional WEAVE, X and Y hatch vectors on the nth layer having a cured line width, L, are drawn with their respective centerlines a distance H from the centerlines of their nearest neighbors. The cured lines are separated from one another by a distance S = H - L. On the next layer the procedure is repeated with the centerline of a vector, on the (n + 1)th layer, lying directly

above the centerline of a corresponding vector on the nth layer. This procedure is then continued on all layers. The result is that at the intersections of the X and Y vectors, the doubly cured points sit directly above one another and the spaces between the doubly cured points sit directly above one another. Thus, conventional WEAVE is analogous to building a wall with bricks stacked directly on top of one another. On the other hand, the method of Staggered Weave has the centerline of a given vector on the (n + 1)th layer offset or staggered with respect to the corresponding vector on the nth layer. Furthermore, the amount of offset, from layer to layer, is approximately H/2. Thus, a doubly exposed point on the (n + 1)-th layer is positioned midway between the four neighboring doubly exposed points on the nth layer. Therefore, STAGGERED WEAVE is analogous to building a wall with the positions of the bricks offset from those on the previous layer. When using WEAVE, with some photopolymeric resins, microcracks have been observed between adjacent vector lines. These microcracks have been eliminated by use of Staggered Weave. Of course other patterns of staggering are possible including for example 3 or 4 layer patterns.

The retracted hatch used with Star Weave involves drawing vectors so that each is attached to only the border at its initiation point, and is retracted by a small distance, R, from the border on its opposite or termination end. The optimum retraction distance may be building material (e.g., resin) dependent but can readily

be determined by building several diagnostic parts with different amounts of retraction with a given building material and thereafter determining which retraction values are associated with the most accurately formed parts. Furthermore, the retraction itself should alternate between adjacent vectors and possibly between layers. For example, the first X vector might be attached at a right border, and retracted by an appropriate amount (e.g., 0.025 to 1.3 mm, and preferably 0.38 mm to 0.76, and more preferably approximately 0.50 mm or less) from the left border. As previously noted, the adjacent vector (or some alternating pattern of vectors) will be attached to the left border and retracted from the right border. A similar retraction technique is used for the Y-vectors. Advantages of retracted hatch include reduced internal stresses during part building, reduced stresses on supports with a corresponding reduction in likelihood of catastrophic support failure, reduced time dependent post post-cure distortion, known as "creep", and improved overall part accuracy.

A first implementation of this aspect of the invention is based software generation and output of hatch and fill vectors according to the rules of one of the above embodiments or the like. The software can form the hatch or/and fill vectors and output them to a file after correctly ordering them or alternatively the software can form the hatch or/and fill vectors substantially as they are needed and output these vectors directly to a scanner system for

controlling the solidification of the material. Vector generation and ordering can also be handled by appropriately configured hardware.

The fourth aspect of the present invention includes improved stereolithographic exposure techniques which involve a combination of a fast shutter (e.g. an acousto-optic shutter) and creative scanning techniques. This aspect of the invention is applicable to both rotational scanning systems and translational scanning systems. This aspect of the invention has several advantages over the conventional scanning techniques of stereolithography: 1) improved generation of sharp object features, 2) ability to use less expensive scanners to generate high resolution parts, 3) improved part accuracy by improved exposure, 4) smaller laser beam spot size at the working surface, 5) longer scanner life time, 6) improved part accuracy by improved positional accuracy of a scanner-encoder system due to more nearly constant mirror rotational velocities during part exposure and 7) significantly reduced scanning times when compared to that for raster scanning techniques.

Disadvantages of conventional stereolithography exposure systems involve limited maximum angular acceleration of the scanning mirror systems. The first disadvantage involves the inability to uniformly expose a line of material if the laser scanning system must accelerate or decelerate during the exposure process. This need for acceleration during exposure and limits on the actual

acceleration obtainable lead to a maximum scanning speed. This maximum scanning speed is based on the necessity of maintaining a relatively uniform exposure over the length of a vector, thereby limiting one to periods of, and lengths of acceleration, that are relatively short.

The second disadvantage with conventional scanning techniques involves the ability to form sharp features. When drawing sharp features with a vector scanning system, the maximum angular acceleration capability and/or the ability of the servo/scanner system limit the accuracy of the sharp feature. These features exhibit some finite radius, and sometimes, some overshoot or ringing behavior beyond the sharp feature which corresponds to unwanted exposure. In order to limit these inaccuracies, scanners with high acceleration capability must be used, and elaborate servo-drivers must be developed and optimized for both regular and sharp feature performance. Higher acceleration scanning systems are more costly and dual role servo optimization (for both regular and sharp features) limits performance with regular features.

Spot size is also compromised as the rotating inertia (moment of inertia) of the mirror must be reduced to maintain necessary system acceleration capability. This precludes the use of larger mirrors with existing scanners that would allow a larger beam size (smaller f/number) and allow a smaller focused spot size at the resin surface.

Scanner lifetime is also compromised by the peak bearing loads which are generated during these sharp-feature maneuvers.

A primary feature of this aspect of the invention involves shuttering the beam when the beam needs to make a significant change in scanning velocity, i.e. scanning direction and/or speed, or needs to travel over a region which isn't supposed to be exposed. By shuttering the beam when these target points of non-exposure, change of direction, or change of speed are reached, the scanning system is allowed to overshoot the target point and decelerate or accelerate (including constant speed changes of scanning direction) while beyond the target point and outside the area to be exposed. After bringing the scanning system and therefore the beam up to or down to the appropriate exposure speed along the appropriate exposure path and passing the beam across the target point the shutter is reopened so the beam can expose the working surface to properly transform the building medium.

A particular embodiment of this aspect of the invention involves the following steps:

1) Before drawing or while drawing vector n, at a particular drawing speed and direction, evaluate vector n+1 to determine any necessary modifications to the scanning parameters that will need to be made. These scanning parameter changes involve the determination of whether or not vector n and vector n+1 meet head to tail, whether vector n and n+1 are to be exposed utilizing the

same scanning speed, and whether or not there is a change in scanning direction between the two vectors which requires a significant acceleration. If vector n and n+1 meet head to tail proceed to step 2a, if they do not meet head to tail proceed to step 2b.

2a) With regard to vectors that meet head to tail, an approximate laser path radius at an up-coming sharp feature is computed. This computation may involve the scanning speed, or change thereof, and the change in scanning direction (angle). The purpose of the computation is to predict a radius based on the desire to keep potential scanning inaccuracies at a tolerable level. These inaccuracies include speed inaccuracies as well as positional inaccuracies at this junction. The speed inaccuracies are preferably maintained below a level which results in cure depth errors of less than 0.050mm and more preferably 0.025mm. The positional inaccuracies are preferably maintained below a level which would result in solidifying material which is more than 0.050 or 0.076mm out of position and more preferably below a level which would result in solidifying material which is more than 0.025mm out of position and most preferably below a level which would result in an error.

3a) Determine whether the predicted radius is less than or greater than a preset maximum radius limit. If less than the preset radius limit the transition from vector n to vector n+1 is made by the conventional method of scanning. If the predicted radius is greater than the

preset maximum limit, the shutter is closed at the sharp corner junction, and the scanning system continues scanning across the junction in the same direction as that scanned for vector n. Before beginning scanning or while approaching the junction, or heading away from it, a trajectory is determined which will bring the scanning direction and speed in line with the desired position, scanning direction and speed for vector n+1. When the scanners repoint the beam toward the junction point, while traveling along the desired path at the desired speed the shutter is opened and vector n+1 is scanned. The determined trajectory can be made to minimize the arc of rotation with which the beam would scan on the working surface if it were not shuttered. Alternatively, the beam can simply be commanded to jump to a point located on the line of vector n+1 and at such a distance from the beginning point of vector n+1 such that the beam is directed toward the beginning point and by the time it gets there it is stably traveling at the desired velocity.

4a. Continue this process by storing necessary information or exposing vector n+1 and evaluating vector n+2. Therefore in the above steps replace n+1 with n+2 and replace n with n+1.

2b. With regard to vectors that do not meet head to tail, the shutter is closed as the junction point is crossed. The scanning system continues scanning across the junction in the same direction as that scanned for vector n. Before scanning or while approaching the

junction or heading away from it, a trajectory is determined which will bring the scanning direction and speed in line with the desired beginning position, scanning direction, and speed for vector n+1. When the scanners point the beam toward the beginning point of vector n+1, while traveling along the desired path at the desired velocity the shutter is opened and vector n+1 is scanned.

3b. Continue this process by storing information or exposing vector n+1 and evaluating vector n+2. Therefore, in the above step replace n+1 with n+2 and replace n with n+1.

Figures 8a to 8g show various orientations of vector n and vector n+1, 900 and 904 respectively, along with shuttered (virtual) scanning paths while maintaining a constant scanning speed and implementing a maximum tolerable acceleration which is indicated by 908. Alternatively these shuttered paths 912 can be modified by allowing for a change in scanning speed before and after the change in scanning direction (angular acceleration of the beam on the working surface). The scanning speed can be reduced after shuttering occurs and before the attempted angular acceleration and then increased prior to reopening the shutter. As indicated this may allow for shorter virtual scanning paths by allowing for a tighter turning radius. Figures 8a, b, c, and e show constant speed virtual paths for different types of junctions using a maximum allowed value of angular acceleration. Figures 8d and e show virtual paths wherein the scanning speed is linearly

decelerated and accelerated prior to the angular acceleration involved in changing directions (smaller turning radii). Alternatively, Figures 8d and e can be viewed as depicting virtual paths in which there is a change in speed during the virtual scan to accommodate a desired change in scanning velocity between the two vectors.

Other alternative approaches include:

1) Any combination of moves beyond the junction that reduce the maximum mirror acceleration. For example, as indicated above, as a sharp feature gets sharper and approaches a 180 degree turn, the technique of constant velocity and minimum turning may result in unacceptable time delays (e.g. Figure 8e). Therefore a computationally more complex embodiment can be implemented where there isn't an attempt to minimize the magnitude of the angular rotation. An example of this type of embodiment is shown in Figure 8g, wherein the virtual scan begins with a slight angular acceleration in the direction opposite to that which would directly bring the scanning path parallel to the appropriate direction. This type of virtual scan is known as an "airplane style" turn. The benefit of this use of opposite angular acceleration is in the reduced scanning path length and therefore reduced virtual scanning time. This airplane type of turn is appropriate for scanning hatch and fill type vectors wherein there is a short gap between the vectors and a required 180 degree turn.

2) Use of two stage scanning, wherein coarse scanners are limited to some preset acceleration, while limited range fast scanners "sharpen up" the corners. Acousto-optic crystal modulators act as frequency controlled diffraction gratings, by varying standing waves within the crystal, and can be used to deflect a beam slightly for fine position adjustments or to deflect it sufficiently into a beam trap, thereby acting as a shutter. Therefore, a pair of acousto optic modulators or the like can function as both shutters and fine adjust scanners. An example of another candidate for fine adjustment scanners are piezoelectric crystal mirrors that can be mounted in front of or on the course of the main scanning mirrors.

A first implementation of this aspect of the invention is based on having the program that generates the vector data for exposing a layer also generate and supply additional non-exposure vector data that indicates when shuttering is to occur, the path to be followed by the beam when no exposure occurs to align the path and velocity for the next exposure vector, and indicating when the shutter should be reopened.

A second implementation of this embodiment is based on using vector exposure data combined with scanning mirror control software or hardware that compares the velocity, end point and scanning direction of a first vector to the velocity, beginning point and scanning direction of a

second vector and determines when shuttering and/or virtual scanning is necessary.

In either implementation virtual scanning after leaving the first vector and before beginning exposure of the second vector can be fully controlled or only partially controlled. In the closed shutter mode the exact path of travel of the beam is not critical as long as the path and velocity are adjusted to meet the beginning point of the second exposure vector along the appropriate direction and at the appropriate speed. In other words, after crossing the endpoint of the first vector and closing the shutter, the scanning system can be commanded to simply jump to a new virtual vector beginning point which is close enough to the beginning point of the second vector so that little time is wasted during the virtual scan, yet lined up with the second exposure vector and far enough from the beginning point of the second vector such that sufficient time is available for the beam position and velocity to stabilize before encountering the beginning point.

Alternative embodiments include any combination of exposure vectors created during the scanning as needed or in advance, and creation of non-exposure vectors during scanning. For computational simplicity all vectors can be followed by virtual scanning followed by realignment for scanning the next exposure vector. However, it is more preferred to allow at least continuous exposure scanning when vectors meet head to tail along the same line. It is

even more preferable to allow continuous scanning when vectors meet head to tail with only a slight acceleration (an acceleration that results in a minimal change in cure depth of the material being exposed by the beam, preferably less than 2 mil change in cure depth and more preferably less than 1 mil change in cure depth) required to change velocity or direction.

It is presently preferred for maintaining maximum beam power to use the zeroth order mode of the acousto-optic modulator for exposure and a first order deflection when in the non-exposure mode. However, when the beam is in the first order mode, the zeroth mode doesn't completely vanish, thus exposure can still occur. If in a given application the attenuation coefficient isn't high enough when going from zeroth order "on" to first order "off", at the cost of reduced beam intensity, the on/off orders and optical paths can be reversed thereby allowing an infinite attenuation coefficient.

While four aspects of the invention have been separately presented, a fifth aspect of this invention includes any combination of the above four aspects. It will be apparent to those skilled in the art that numerous combinations of the sets can be made which result in further improvements in the production of stereolithographic parts. In particular it is noted that aspect four can be combined with aspects one through three for better control of exposure and that aspects one through three can be combined in pairs or as a trio.

The four aspects of the invention should be used to the extent necessary or desired to achieve sufficient reduction in distortion.

Additionally, all four aspects of the invention are equally applicable to upside down building techniques as well as the right side up techniques as well as to different types of building materials including liquid polymers, sinterable powders, and bindable powders. All aspects of the invention are also applicable to exposure technique that use scanning paths controlled by other than vectors. It will also be apparent that the three-dimensional objects to be formed by this invention can be used in many ways. For example they can be used as final products for certain applications, or as patterns for reproduction of the object out of other materials, or as patterns for forming necessary tooling for high volume reproductions of an object.

We Claim:

1. In a stereolithographic method for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising the step of forming successive layers of medium in preparation for forming layers of the object and the step of forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure, the improvement comprising the steps of:

leaving breaks of unexposed material along a first plurality of paths while exposing at least a portion of a first layer along said first plurality of paths to a first pass of a beam of synergistic stimulation to cause solidification of the building material along said first plurality of paths;

leaving breaks in exposure along a second plurality of paths within said portion when exposing said second plurality of paths to at least a second pass of a beam of synergistic stimulation wherein a substantial number of breaks in exposure along said second plurality of paths occur at different locations than said breaks in exposure along said first plurality of paths and wherein said second pass reexposes material cured on said first pass

only after said material being reexposed has been allowed to undergo a substantial portion of any shrinkage induced by said first pass.

2. The method of claim 1 wherein said first pass along said first plurality of paths causes a depth of solidification less than that necessary to cause adhesion to a previously formed layer.

3. In a stereolithographic apparatus for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising means for forming successive layers of medium in preparation for forming layers of the object and means for forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure, the improvement comprising:

means for exposing at least a portion of a layer to a beam of synergistic stimulation along a first plurality of paths;

means for leaving small breaks of unexposed and unsolidified material along said first plurality of paths while exposing said at least portion of said layer along said first plurality of paths to a first pass of a beam of synergistic stimulation to cause solidification of the

building material along said first plurality of paths;

means for exposing at least a portion of a layer to a beam of synergistic stimulation along a second plurality of paths;

means for leaving small breaks in exposure along said second plurality of paths, within said at least portion, when exposing said second plurality of paths to at least a second pass of a beam of synergistic stimulation wherein a substantial number of breaks in exposure along said second plurality of paths occur at different locations than said breaks in exposure along said first plurality of paths; and

means for causing said second pass to reexpose material cured on said first pass only after said material to be reexposed has been allowed to undergo a substantial portion of shrink induced by said first pass.

4. In a stereolithographic method for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising the step of forming successive layers of medium in preparation for forming layers of the object and the step of forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the improvement comprising the steps of:

forming at least a portion of at least one layer of the three-dimensional object from tiles which are separated from one another by gaps; and

solidifying a substantial portion of the material above at least one gap on at least one next layer by exposing the material above the gap and leaving at least one side of the gap unadhered to the material solidified over the substantial portion of the gap until after said solidified material over the gap has been allowed to shrink and thereafter causing adhesion to occur between the previously unadhered side of the gap and the solidified material over the gap.

5. In a stereolithographic apparatus for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising means for forming successive layers of medium in preparation for forming layers of the object and means for forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the improvement comprising:

means for forming at least a portion of at least one layer of the three-dimensional object from tiles which are separated from one another by gaps; and

means for solidifying a substantial portion of

the material above at least one gap on at least one next layer including means for exposing the material above the gap and means for leaving at least one side of the gap unadhered to the material solidified over the substantial portion of the gap until after said solidified material over the gap has been allowed to shrink and means for thereafter causing adhesion to occur between the previously unadhered side of the gap and the solidified material over the gap.

6. In a stereolithographic method for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising the step of forming successive layers of medium in preparation for forming layers of the object and the step of forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure, the improvement comprising the steps of:

forming at least portions of a plurality of layers by exposing at least two of said plurality of layers each along at least one set of paths and altering the order in which the at least one set of paths is exposed over the at least two layers.

7. The method of claim 6 wherein the at least one set of paths is at least two sets of vectors wherein each of the at least two sets is composed of parallel vectors wherein the vectors in one set are not parallel to the vectors in another set.

8. The method of claim 7 wherein the order of scanning the at least two sets of vectors is altered between at least two layers by altering at least one of the exposure order between the two sets or the selection of a beginning and ending side within a single set.

9. In a stereolithographic apparatus for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising means for forming successive layers of medium in preparation for forming layers of the object and means for forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the pattern including paths of exposure, the improvement comprising:

means for forming at least portions of a plurality of layers by exposing each of at least two of said plurality of layers along at least one set of paths and means for altering the order in which the at least one set of paths is exposed over the at least two layers.

10. In a stereolithographic method for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising the step of forming successive layers of medium in preparation for forming layers of the object and the step of forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure defined by vectors, the improvement comprising the steps of:

identifying an end point of a first vector and a beginning point of a second vector wherein a substantial difference in scanning velocity is required for traversing the first and second vectors;

scanning the synergistic stimulation along the first vector at a substantially fixed velocity;

shuttering the synergistic stimulation when it reaches the endpoint of the first vector without significantly varying the substantially fixed velocity;

redirecting the synergistic stimulation in a pattern which varies the velocity of said scanning from that required for the first vector to that required for the second vector and which causes the scanning path to cross-over the beginning point of the second vector while traveling at the desired velocity for the second vector;

unshuttering the synergistic stimulation when it crosses the beginning point of the second vector; and

scanning the synergistic stimulation along the second vector.

11. The method of claim 10 wherein the substantial difference in scanning velocity is a difference in scanning direction.

12. The method of claim 10 wherein the substantial difference in scanning velocity is a difference in scanning speed.

13. The method of claim 10 wherein the substantial difference in scanning velocity is a difference in scanning speed and in scanning direction.

14. The method of claim 10 wherein the endpoint of the first vector is coincident with the beginning point of the second vector.

15. The method of claim 10 wherein the endpoint of the first vector is not coincident with the beginning point of the second vector.

16. The method of claim 10 wherein the substantial difference in scanning velocity is a difference which would cause a change in cure depth by more than .025mm

when the transistion from the first velocity to the second velocity occurs under the maximum acceleration possible which results in less than a .025mm error in scanning position.

17. An improved stereolithographic apparatus for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising means for forming successive layers of medium in preparation for forming layers of the object and means for forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure defined by vectors, the improvement comprising:

means for identifying an end point of a first vector and a beginning point of a second vector wherein a substantial difference in scanning velocity is required for traversing the first and second vectors;

means for scanning the synergistic stimulation along the first vector at a substantially fixed velocity;

means for shuttering the synergistic stimulation when it reaches the endpoint of the first vector without significantly varying the substantially fixed velocity;

means for redirecting the synergistic stimulation in a pattern which varies the velocity of said scanning

from that required for the first vector to that required for the second vector and which causes the scanning path to cross-over the beginning point of the second vector while traveling at the desired velocity for the second vector;

means for unshuttering the synergistic stimulation when it crosses the beginning point of the second vector; and

means for scanning the synergistic stimulation along the second vector.

18. An improved stereolithographic method for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising the step of forming successive layers of medium in preparation for forming layers of the object and the step of forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure defined by vectors, the improvement comprising the steps of:

identifying an end point of a first vector and a beginning point of a second vector wherein the beginning point of the first vector is different from the ending point of the second vector;

scanning the synergistic stimulation along the

first vector at a substantially fixed velocity;

shuttering the synergistic stimulation when it reaches the endpoint of the first vector without significantly varying the substantially fixed velocity;

directing the synergistic stimulation, while it is shuttered, in a pattern to the beginning point of the second vector and that the proper velocity for exposing the second vector is achieved when the beginning point of the vector is reached. unshuttering the synergistic stimulation when it reaches the beginning point of the second vector; and

scanning the synergistic stimulation along the second vector.

19. An improved stereolithographic apparatus for constructing a three-dimensional object from a medium solidifiable upon exposure to synergistic stimulation, comprising means for forming successive layers of medium in preparation for forming layers of the object and means for forming successive layers of the object by selectively exposing said successive layers of medium to synergistic stimulation in patterns corresponding to successive cross-sections of the three-dimensional object, to build up the three-dimensional object layer by layer, the patterns including paths of exposure defined by vectors, the improvement comprising:

means for identifying an end point of a first vector and a beginning point of a second vector wherein

the beginning point of the first vector is different from the ending point of the second vector;

means for scanning the synergistic stimulation along the first vector at a substantially fixed velocity;

means for shuttering the synergistic stimulation when it reaches the endpoint of the first vector without significantly varying the substantially fixed velocity;

means for directing the synergistic stimulation, while it is shuttered, in a pattern to the beginning point of the second vector and that the proper velocity for exposing the second vector is achieved when the beginning point of the vector is reached;

unshuttering the synergistic stimulation when it reaches the beginning point of the second vector; and

means for scanning the synergistic stimulation along the second vector.

1/6

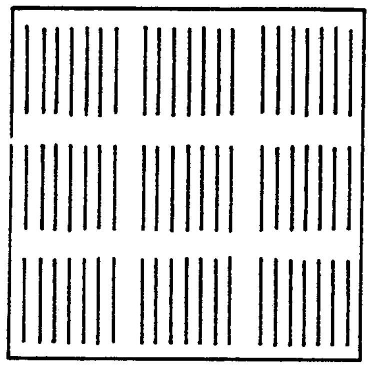


FIG. 1a.

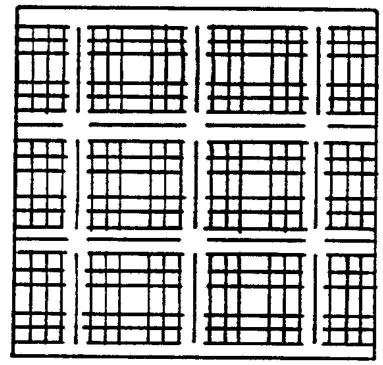


FIG. 1b.

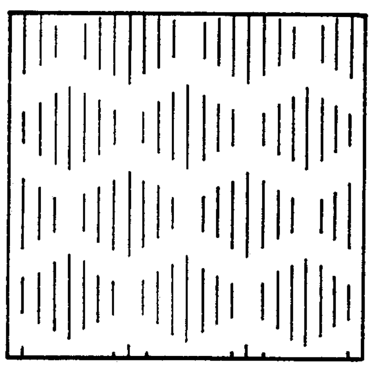


FIG. 2a.

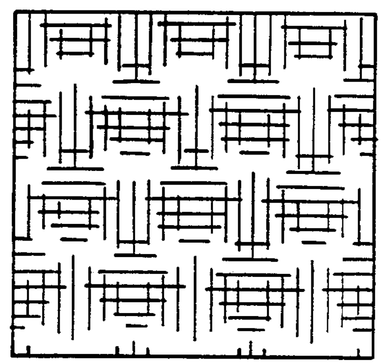


FIG. 2b

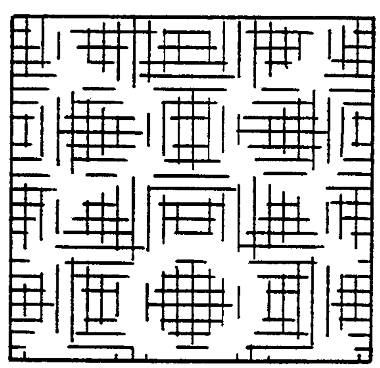


FIG. 2c.

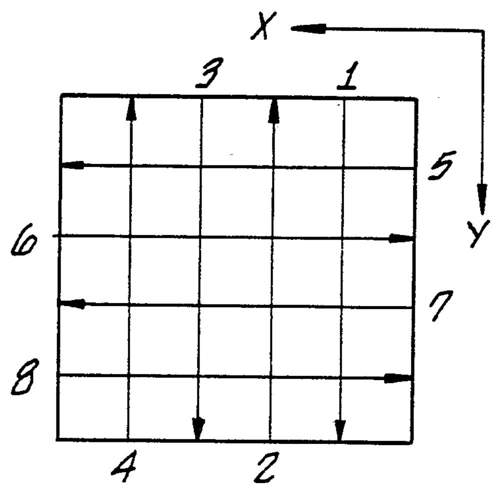


FIG. 3.

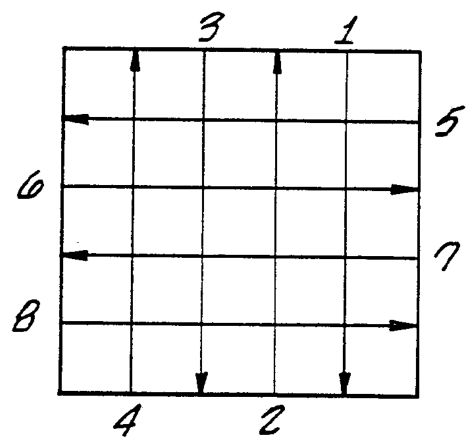


FIG. 4a.

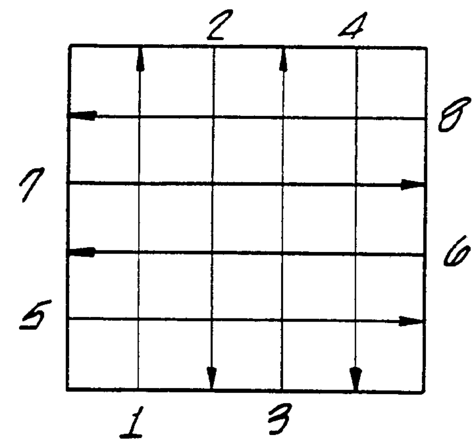


FIG. 4b.

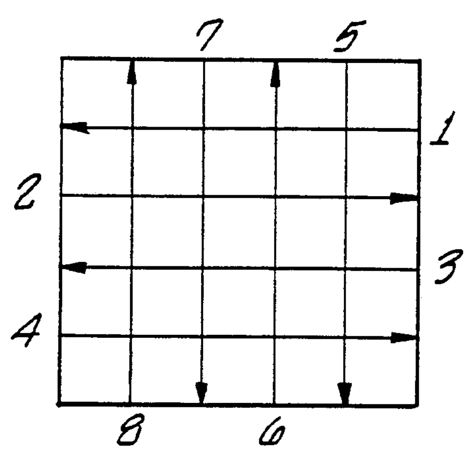


FIG. 4c.

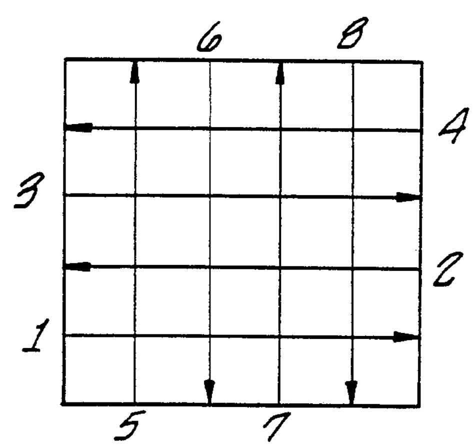


FIG. 4d.

3/6

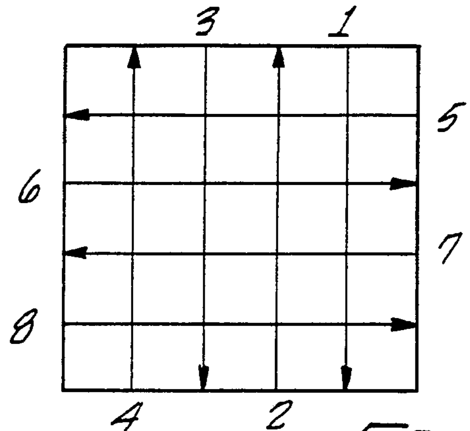


FIG. 5a.

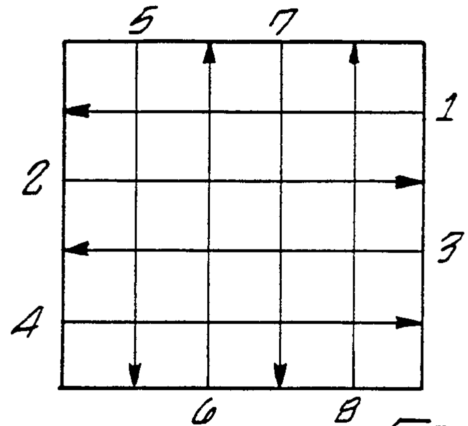


FIG. 5d.

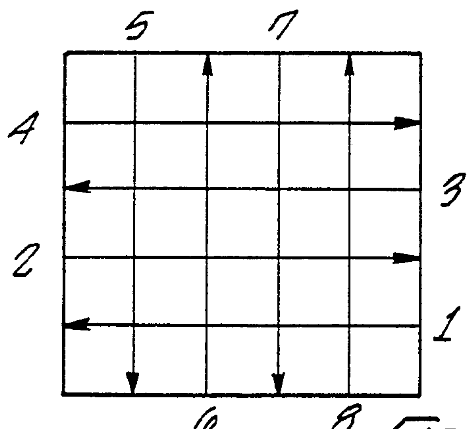


FIG. 5b.

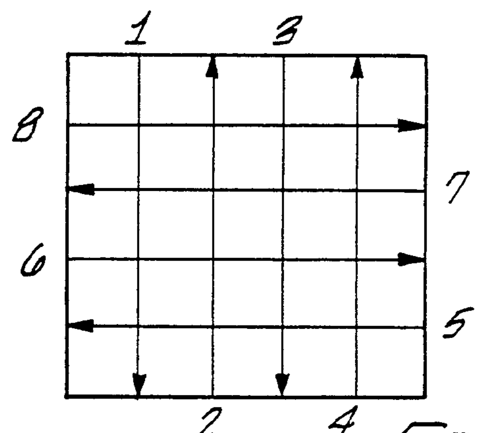


FIG. 5e.

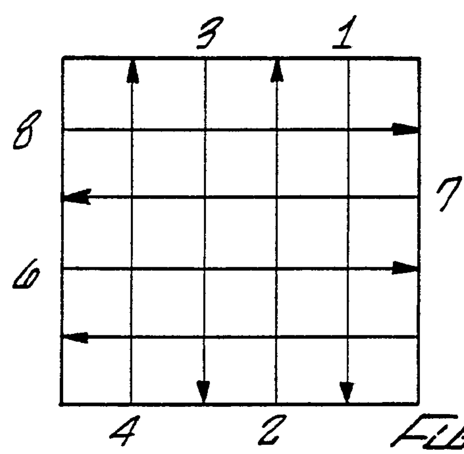


FIG. 5c.

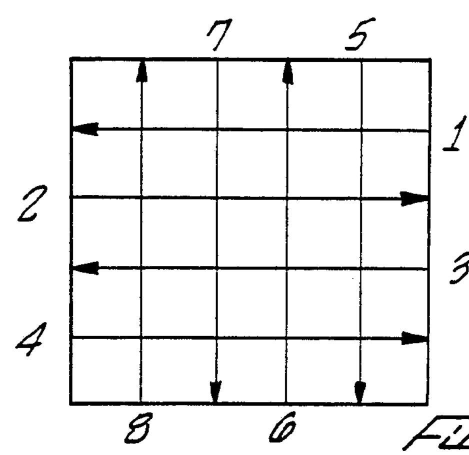


FIG. 5f.

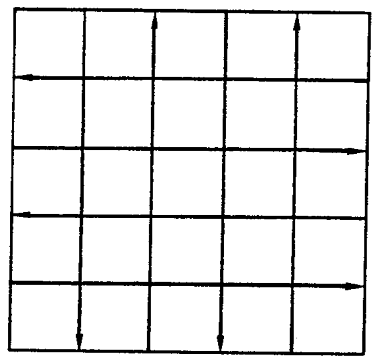


Fig. 5g.

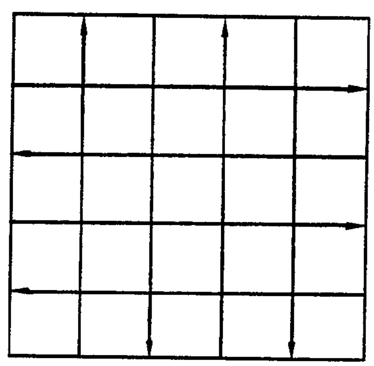


Fig. 5h.

5/6

FIG. 6a.

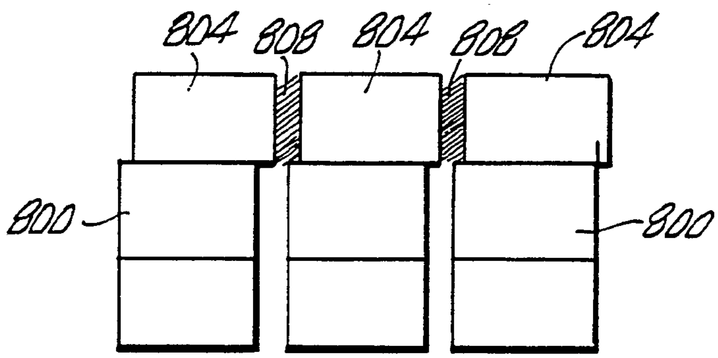
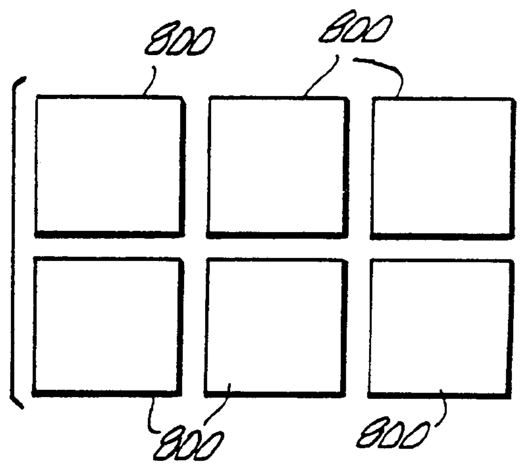


FIG. 6b.



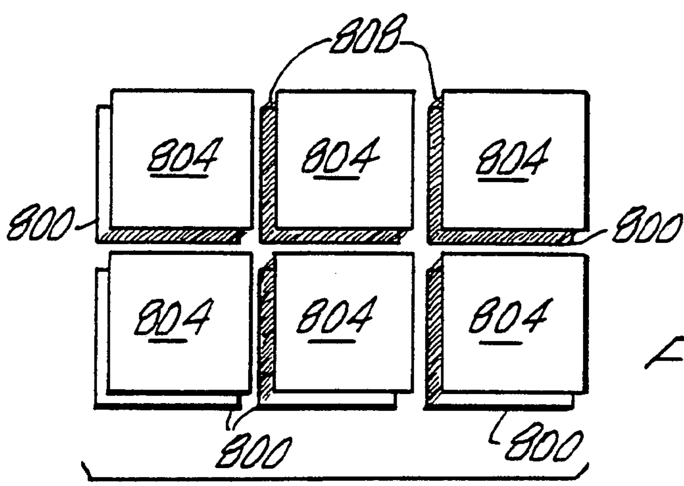


FIG. 6c.

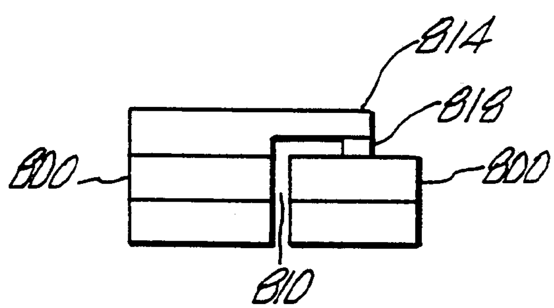


FIG. 7.

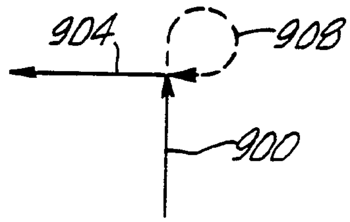


FIG. 8a.

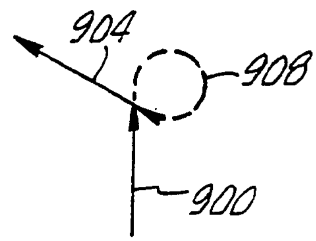


FIG. 8b.

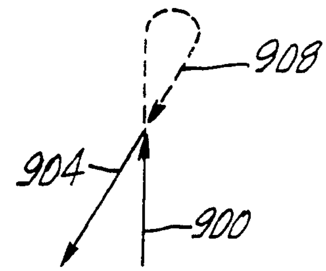


FIG. 8c.

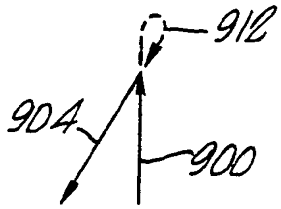


FIG. 8d

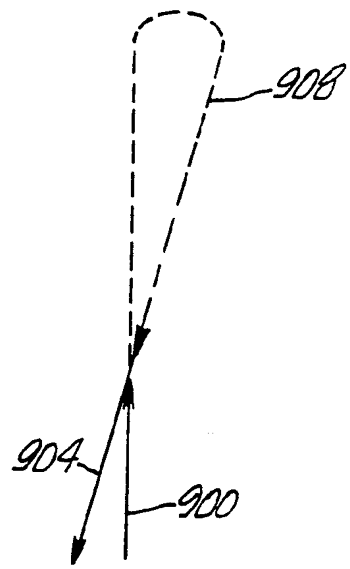


FIG. 8e.

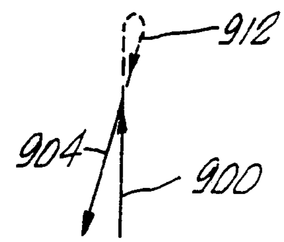


FIG. 8f.

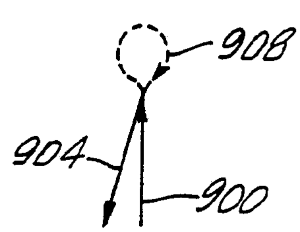


FIG. 8g.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/04107

A. CLASSIFICATION OF SUBJECT MATTER
IPC(5) : B29C 35/08, 41/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 156/273.3, 273.5, 275.5, 290, 307.1; 250/492.1; 264/22, 308, DIG. 59; 364/476; 365/106, 107; 427/53.1, 54.1

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US, A, 4,575,330 (HULL) 11 March 1986.	1-19

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be part of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search: 08 JULY 1992

Date of mailing of the international search report: 25 SEP 1992

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Form PCT/ISA/210 (second sheet)(July 1992)★